2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation

Paper Number: 084098

Simulating Methane Emissions from Dairy Farms

Dawn Sedorovich Chianese, Associate

Environ Corporation, 707 Wilshire Blvd., Suite 4950, Los Angeles, CA 90017

C. Alan Rotz, Agricultural Engineer

USDA / ARS, Building 3702, Curtin Road, University Park, PA 16802

Tom L. Richard, Associate Professor

Agricultural and Biological Engineering Dept., The Pennsylvania State University, University Park, PA 16802

Written for presentation at the
2008 ASABE Annual International Meeting
Sponsored by ASABE
Rhode Island Convention Center
Providence, Rhode Island
June 29 – July 2, 2008

Abstract. *As a sector, agriculture is reported to be the third greatest contributor of methane in the U.S., emitting one-quarter of total emissions. The primary sources of methane on dairy farms are animals and manure storages with smaller contributions from field-applied manure, feces deposited by grazing animals, and manure on barn floors. The Integrated Farm System Model was expanded to include simulation of methane emissions from enteric fermentation and the other farm sources. In simulating a representative 100-cow dairy farm in Pennsylvania, the model predicted a total average annual emission of 20 Mg CH_4. This included an average annual emission of 135 kg CH_4 per cow from the Holstein herd and an average emission of 5.4 kg CH_4 per m^3 of stored slurry manure, which were very similar to previously reported emissions. This expanded whole-farm model can be effectively used to evaluate proposed methane reduction strategies along with their impact on other environmental and economic issues.*

Keywords. Methane, Greenhouse gas, Dairy farm, Simulation model.

Introduction

In 2007, the Intergovernmental Panel on Climate Change (IPCC, 2007) reported that it is "extremely likely" (i.e., representing a 95% confidence level or higher) that anthropogenic emissions of greenhouse gases (GHGs) are causing a change in the global climate. Although many mitigation plans currently focus on reducing carbon dioxide (CO_2) emissions, methane (CH_4) is a stronger greenhouse gas and has a global warming potential around 23 times that of CO_2 (IPCC, 2007). The Food and Agriculture Organization of the United Nations has claimed that livestock emit more CH_4 in CO_2 equivalents than is emitted through the burning of fossil fuels for transportation (FAO, 2006). In 2005, agriculture was reported to contribute 25% of the total U.S. CH_4 emissions, behind only the energy sector (39%) and human waste management (36%) in overall impact (EIA, 2006). As a result, quantifying and reducing CH_4 emissions from livestock farms is important in reducing overall CH_4 emissions.

Multiple processes emit CH_4 from dairy farms including enteric fermentation in animals and microbial processes in manure. A review of agricultural emission data shows that the majority of CH_4 from dairy farms is created through enteric fermentation, followed by emissions from manure storages (Sedorovich et al., 2007). In addition to these major sources, less significant emissions result from field-applied manure and from manure deposited by animals inside barns or on pasture. Recent research has shown that plants may also emit CH_4, although the mechanism is not currently known (Keppler and Röckmann, 2007). Field studies (e.g., Sherlock et al., 2002), as well as our review of agricultural emissions (Sedorovich et al., 2007), report croplands as a negligible source, or small sink, of CH_4 in the long term. However, field-applied slurry can result in significant emissions for a few days after application (Chadwick and Pain, 1997; Sherlock et al., 2002).

Computer simulation can provide a cost-effective and efficient method of estimating CH_4 emissions from dairy farms and analyzing how management scenarios affect these emissions. The Integrated Farm System Model (IFSM), a model developed by the USDA's Agricultural Research Service (ARS), is a process-based whole-farm simulation including major components for soil processes, crop growth, tillage, planting and harvest operations, feed storage, feeding, herd production, manure storage, and economics (Rotz et al., 2007). IFSM predicts the effect of management scenarios on farm performance, profitability and environmental pollutants such as nitrate leaching, ammonia volatilization, and phosphorus runoff loss. Expansion of the model to included GHG emissions will enhance its application.

The overall objective of this research was to incorporate a module into IFSM that simulated emissions of CH_4, to obtain a tool for quantifying CH_4 emissions from dairy farms and evaluating how management scenarios affect these emissions. Specific objectives were to review published models that simulate CH_4 emissions, identify relationships that best fit our modeling goals, adapt those models for use in IFSM, and demonstrate the use of this tool in predicting whole-farm CH_4 emissions and the impacts of reduction strategies.

Model Development

Enteric fermentation and manure storage are the major sources of CH_4 from farms, contributing about 63% and 30% of total agricultural CH_4 emissions, respectively (EIA, 2006). Even though manure applied on fields, feces deposited on pasture, and manure on barn floors do not contribute large amounts of CH_4, we included relationships to simulate these emissions to obtain a comprehensive prediction of farm-level emissions. A number of models have been published that predict emissions from the major sources. To create our module, we selected relationships that best fit our needs for whole-farm simulation. Criteria used to evaluate potential models were:

1. The model had to be capable of simulating important processes that affect CH_4 emissions with changes in farm management. Strategies to reduce CH_4 emissions from enteric fermentation primarily involve animal diet. Strategies to reduce CH_4 emissions from manure storages include storage covers and capturing and flaring the gas. In order to analyze how these and other practices affect CH_4 emissions, the model had to account for the associated processes (e.g., animal ration, manure type, and storage design).

2. The model had to provide a process-level representation of emission components. Several published models, as well as the IPCC, predict CH_4 emissions from farms using emission factors (e.g., Schils et al., 2005; Lovett et al., 2006). While these models are useful as simple tools for estimating CH_4 emissions from farms, they do not have the capability of representing processes that affect CH_4 emissions. For example, Schils et al. (2005) simulated CH_4 emissions due to enteric fermentation in heifers and calves by multiplying a group-specific emission factor by the number of animals in each group. This model only accounted for the effect of reducing or increasing animal numbers and would not account for diet modifications. As a result, our goal was to select physically- and biologically-based relationships that satisfied criterion 1 as compared to models based on emission factors.

3. The model had to satisfactorily predict observed data over a full range of potential conditions. A primary goal of models is to simulate observed data. The chosen relationships had to predict CH_4 emissions within the range of observed emissions from farm components over the full range of possible farm characteristics.

4. The model had to be consistent with the current scale of other components in IFSM. The intent of IFSM is to simulate realistic management scenarios that can be implemented on farms. The characteristics of these scenarios are designated at a farm scale (e.g., animal diets, sequence of machinery operations, manure storage duration). Subsequently, IFSM simulates processes, normally on a daily time step, at the field- or farm-level according to the assumed farm characteristics. As a result, selected relationships, as well as associated inputs and parameters, had to function well at the field- or farm-level as opposed to different scales (e.g., microbiological or watershed).

5. Model inputs and parameters were limited to readily available data. Some of the available mechanistic models predict emissions with accuracy; however, these models typically require many inputs and parameters. The required values are often the result of calibrating the model against observed data, are difficult to obtain, or have no physical or biological basis. The uncertainty added by assuming these parameter values can outweigh the benefit of using a highly mechanistic model. In contrast, the majority of parameters and inputs in IFSM are not calibration parameters, are relatively easily obtained through on-farm observations, and correspond to characteristics of the farm. Thus, our final criterion was that input and parameter values were easily obtained within, or consistent with, the current structure of IFSM.

Enteric Fermentation

Ruminant animals subsist primarily on forages like grasses and leafy plants. Like most animals, ruminants do not have the enzymes necessary to break down cellulose. Instead, enteric methanogens exist in a symbiotic relationship with other microorganisms in the rumen and, through enteric fermentation, break down and obtain energy from cellulose. In the rumen, enteric methanogens prevent the build-up of the hydrogen produced during fermentation by reducing CO_2 to CH_4. The CH_4 produced is released to the atmosphere by eructation, or belching. Other roles of these microorganisms are not fully understood (Madigan et al., 2003).

The amount of CH_4 produced from enteric fermentation is impacted by various factors including animal type and size, digestibility of the feed, and the intake of dry matter, total carbohydrates, and digestible carbohydrates (Monteny et al., 2001; Wilkerson et al., 1995).

Because of the potential role of CH_4 in climate change, various models have been published that attempt to predict the amount of CH_4 produced by ruminant animals. These models can be categorized as mechanistic or empirical. The more mechanistic models (e.g., Baldwin et al., 1987; Dijkstra et al., 1992; Mills et al., 2001) are based on the chemical or microbiological processes occurring in the rumen that produce CH_4. These models are highly detailed and require many state variables and equations to simulate CH_4 emissions. For example, Dijsktra et al. (1992) utilized 17 state variables and more than 100 equations to simulate enteric fermentation. Empirical models are based on equations relating CH_4 emissions to various factors. These models range from equations based solely on statistical correlations to biologically-based relationships.

The first widely used ruminant CH_4 model was an empirical model published by Blaxter and Clapperton (1965, Table 1). Methane production was correlated to feeding (i.e., a multiple of the recommended energy requirement for maintenance) and the digestibility of the animal's diet. Other empirical models have related CH_4 production to feed characteristics (Moe and Tyrrell, 1979), milk yield and live weight (Kirchgessner et al., 1991), dry matter intake and feed characteristics (Yates et al., 2000), and metabolizable energy intake, a maximum potential CH_4 production and feed characteristics (Mills et al., 2003; Table 1).

Reviews of both mechanistic and empirical models have been published (Wilkerson et al., 1995; Benchaar et al., 1998; and Mills et al., 2003). Mechanistic models, such as Mills et al. (2001), have explained more variation as compared to empirical models. Relative to our model criteria, the mechanistic model of Mills et al. (2001) satisfied only criteria 1, 2, and 3. This model simulated CH_4 production by modeling chemical reactions in the rumen, which created more detail then needed or desired for simulating processes at the whole-farm scale. More importantly, the inputs and parameters required by their model were not readily available. To use this model, a number of assumptions had to be made in setting input parameters. These values were not readily available or were poorly defined for the wide range of management strategies found on different farms. As such, the uncertainty added by assuming these parameter values outweighed the benefit of using a mechanistic model.

To better meet the needs of our model, a simpler approach was taken using the Mitscherlich 3 (Mits3) equation developed by Mills et al. (2003). Mits3 is a simplified, process-based model that satisfies all five criteria. The model is based on dietary composition and is capable of accounting for management practices that alter the animal's intake and diet, satisfying criterion 1. Mits3 is process-based, relating CH_4 emissions to dietary intake as well as animal type and size, satisfying criterion 2. When compared to data from the U.S., Mits3 yielded a regression slope of 0.89, an intercept of 3.50 (Mills et al., 2003), and a square root of the mean square prediction error (MSPE) of 34.1%. These results verify that Mits3 can satisfactorily predict emissions for U.S. dairy herds, satisfying criterion 3. In addition, Mits3 predicts realistic emissions at the extremes of the parameter ranges. With zero feed intake, the model predicts zero CH_4 production; at the other extreme of very high feed intake, the nonlinear model predicts that CH_4 emissions approach a maximum. Thus, an additional benefit of the nonlinearity of Mits3 is that the model can be applied to conditions outside those for which it was originally developed without predicting unreasonable emissions. In comparison, linear empirical models can predict unrealistic emissions at high feed intakes (Mills et al., 2003; Kebreab et al., 2006).

Mits3 satisfies criterion 4, as the simpler formulation is consistent with the scale needed for whole-farm simulation. Finally, Mits3 satisfies criterion 5 by requiring only three model inputs that were readily obtained from the feed and animal components of IFSM: the starch content of the diet, the acid detergent fiber (ADF) content of the diet, and the metabolizable energy intake. These three inputs were directly related to the animal's diet and indirectly related to animal size and type. This allowed prediction of changes in CH_4 production as affected by changes in animal nutrition and management.

A detailed description of the selected model can be found in Mills et al. (2003). This section briefly describes the model, parameters for the model, and integration with IFSM.

Emission of CH_4 is predicted as:

$$E_{CH4,ent} = \left[E_{\max} - E_{\max}\exp\left(-c \cdot M_{EI}\right)\right] \cdot F_{kgCH4} \tag{1}$$

where $E_{CH4,ent}$ is the emission due to enteric fermentation [kg CH_4 cow^{-1} day^{-1}], E_{max} is the maximum possible emission [MJ CH_4 cow^{-1} day^{-1}], c is a shape parameter determining how emissions change with increasing M_{EI} [dimensionless], M_{EI} is the metabolizable energy intake [MJ cow^{-1} day^{-1}], and F_{kgCH4} is the conversion of MJ to kg of CH_4 [0.018 kg CH_4 MJ^{-1}]. The maximum possible emission, E_{max}, is defined as 45.98 MJ CH_4 cow^{-1} day^{-1} (Mills et al., 2003).

Table 1. Summary of empirical models simulating CH_4 production through enteric fermentation.

Model	Model core equations[a]	Units
Blaxter and Clapperton (1965)	$E_{CH4,ent}$ = 1.30+0.112*D–L*(2.37–0.05*D) L = multiple of maintenance level D = apparent digestibility	kcal CH_4 per 100 kcal feed
Moe and Tyrrell (1979)	$E_{CH4,ent}$ = 0.439+0.273*R+0.512*H+1.393*C R = residue (kg) H = hemicellulose (kg) C = cellulose (kg)	Mcal CH_4
Kirchgessner et al. (1991)	$E_{CH4,ent}$ = 55+4.5*M+1.2*W (grass) $E_{CH4,ent}$ = 26+5.1*M+1.8*W (corn silage) M = milk yield W = live weight	g CH_4 day^{-1}
Yates et al. (2000)	$E_{CH4,ent}$ = 1.36+1.21*D_m-0.825*D_{mc}+12.8*N_d (all) $E_{CH4,ent}$ = -35.5+0.0216*N+27.6*S_{dm}+1.63*G_{dm} (silage) D_m = dry matter intake (kg) D_{mc} = dry matter concentrates (kg) N_d = ratio of NDF/D_m N = N intake S_{dm} = ratio of silage D_m/D_m G_{dm} = ratio of gross energy/D_m	MJ CH_4 day^{-1}
Mills et al. (2003)	$E_{CH4,ent}$ = E_{max} - E_{max} * exp(-c*M_{EI}) E_{max} = maximum value of CH_4 production c = shape parameter M_{EI} = metabolizable energy intake	MJ CH_4 day^{-1}

[a] $E_{CH4,ent}$ represents the emission of CH_4 from enteric fermentation as simulated by the various models being used. The units of $E_{CH4,ent}$ vary for each model as listed under the units column.

Table 2. Relationships used to model starch and ADF contents of feeds in IFSM.

Feed type	Starch[a],[b] [fraction]	ADF [fraction]
Alfalfa hay	0.64*(1-F_{NDF}-F_{CP}-0.11)	0.78*F_{NDF}
Alfalfa silage	0.89*(1-F_{NDF}-F_{CP}-0.12)	0.82*F_{NDF}
Grass hay	0.45*(1-F_{NDF}-F_{CP}-0.11)	0.61*F_{NDF}
Grass silage	0.65*(1-F_{NDF}-F_{CP}-0.12)	0.64*F_{NDF}
Corn grain	0.68	0.036
High moisture corn	0.52	0.004
Corn silage	0.80*(1-F_{NDF}-F_{CP}-0.07)	0.62*F_{NDF}
Perennial grass/legume	0.48*(1-F_{NDF}-F_{CP}-0.14)	0.72*F_{NDF}
Alfalfa pasture	0.48*(1- F_{NDF}-F_{CP}-0.14)	0.55*F_{NDF}
Protein supplement 1	0.0	0.0
Protein supplement 2	0.0	0.0
Fat additive	0.0	0.0

[a] The last value in the equation in the starch column represents an average total of fat and ash (see Fat + Ash column).

[b] F_{NDF} (fraction of neutral detergent fiber in feed) and F_{CP} (fraction of crude protein in feed) are available in IFSM.

[c] Average values for fat and ash were obtained from NRC (2001).

This maximum possible emission is constant for all animals; the effect of animal size and type is indirectly included in the value of M_{EI}. The shape parameter, c, is calculated as:

$$c = -0.0011 \cdot \left[\frac{Starch}{ADF} \right] + 0.0045 \tag{2}$$

where $Starch$ is the starch content and ADF is the acid detergent fiber content of the diet. Equation 2 models the trend for increased CH_4 emissions with fibrous diets (i.e., high ADF) and decreased emissions with high starch diets.

To use the above equations, three input values were needed: the starch and ADF contents of diets and the metabolizable energy intake of animal groups making up the herd. IFSM determines the ration that each animal group is fed based upon a representative animal's nutritional requirements and the available feeds (Rotz et al., 1999). This information includes the required energy content of the diet [MJ kg DM^{-1}], the total dry matter intake [kg DM day^{-1} cow^{-1}], and the amount of each feed used. The first two parameters were used to calculate M_{EI}. The ADF contents of feeds used in IFSM were calculated assuming a linear relationship with neutral detergent fiber (NDF) for each feed type (Table 2). These relationships were developed using feed composition data from the National Research Council (NRC, 2001). The starch contents of feeds used in IFSM were determined assuming a linear relationship with the amount of nonfibrous carbohydrates (NFC) in the feed (Table 2). The fraction of NFC was determined as:

$$F_{NFC} = 1 - \left(F_{NDF} + F_{CP} + F_{fat} + F_{ash} \right) \tag{3}$$

where F_{NFC} is the fraction of NFC in the diet, F_{CP} is the fraction of crude protein (CP) in the diet, F_{fat} is the fraction of fat in the diet, and F_{ash} is the fraction of ash in the diet. The fractions of NDF and CP were available in IFSM; typical fractions of fat and ash (Table 2) were obtained from the National Research Council (NRC, 2001). A given animal group is normally fed a mixture of feeds making up the whole diet. A weighted average of feeds in the ration was used to determine the starch and ADF contents of the ration fed to each of the six possible animal groups making up the herd (Rotz et al., 1999).

Manure Storage

During manure storage, CH_4 is generated through a reaction similar to that described for enteric fermentation. The cellulose in the manure is degraded, with products of this process serving as substrates for methanogenesis. Temperature and storage time are the most important factors influencing CH_4 emissions from stored manure because substrate and microbial growth are generally not limited (Monteny et al., 2001). Although the processes are similar, there are important differences between the rumen and manure storage. The temperature in a manure storage varies, in contrast to the relatively constant temperature in the rumen, and the manure in storage is more heterogeneous (e.g., the substrate is less well mixed and some carbohydrates are already partially decomposed) as compared to the consistency of the rumen (Monteny et al., 2001).

As with enteric fermentation, both mechanistic and empirical equations have been used to predict CH_4 emissions from manure storages. Unlike some of the empirical enteric fermentation models that simply utilize correlations that are not necessarily based on biological processes, the majority of manure storage models are biologically based. Two mechanistic (Hill, 1982; and García-Ochoa et al., 1999) and four empirical models (Chen and Hashimoto, 1980; Hill, 1991; Zeeman, 1994; and Sommer et al., 2004) were reviewed. Although many models exist, these six models represented those most appropriate for simulating manure storage emissions.

Hill (1982) described a comprehensive and dynamic mechanistic model to predict CH_4 production through animal waste methanogenesis. The model satisfied criteria 1, 2, and 3 of our model requirements. The model was based on biological processes and thus satisfied criterion 2. Input parameters could be changed to account for different reduction strategies, satisfying criterion 1. Model results showed high goodness of fit for dairy manure, satisfying criterion 3. However, the model simulated CH_4 production based on the chemical and microbiological reactions in the storage. As a result, the model scale was not consistent with that of IFSM. Additionally, there were many model parameters that required iterative solutions, and input values that were difficult to obtain.

García-Ochoa et al. (1999) published a mechanistic kinetic model that used three stages to simulate anaerobic digestion and CH_4 production from animal waste. The three stages included 1) the conversion of complex biopolymers to simpler, more accessible substrates, 2) the conversion of hydrolyzed animal waste to volatile organic acids, and 3) the production of CH_4 from volatile organic acids. Assumptions made in developing the model included lumped parameter, pseudo-steady state, and first-order kinetics. This model satisfied criteria 1, 2, and 3. However, the model determined values for ten parameters iteratively using a fourth-order Runge Kutta algorithm linked to a non-linear multiple response regression. Most parameters in IFSM are externally determined and hard-coded, or are set by the user through a graphical interface. The iterative procedure was not consistent with the current structure of IFSM.

Chen and Hashimoto (1980; Table 3) described an empirical model that predicted volumetric CH_4 production from anaerobic digesters. This model satisfied all five criteria. The model was process-based, using a maximum possible CH_4 yield to predict emissions. The model accounted for the reduction of this possible yield due to various factors (e.g., volatile solids concentration, temperature, and hydraulic retention time). When used to predict CH_4 production from the anaerobic digestion of beef cattle manure, the average ratio of experimental to predicted CH_4 production was 0.96 with a standard deviation of ±0.06 (Hashimoto, 1982a).

These results indicated that the model could accurately predict observed data, satisfying criterion 3. The model was also on the same scale as IFSM and utilized readily available data for inputs and parameters (Hashimoto et al., 1981; Hashimoto, 1982b, 1983, and 1984).

Hill (1991; Table 3) described a single equation model to estimate CH_4 production based on volatile solids (VS) reduction. This model was based on Hill (1982), but was intentionally simplified. The model was intended for field use, where computing capabilities were limited, and for undergraduate class simulations, where the goal was to teach students how to calculate CH_4 production rather than what causes the production. The model of Hill (1991) fully satisfied criteria 2 and 3 and partially satisfied criterion 5. The model was based on biological principles using the concentration and reduction of VS. Hill (1991) reported that the simple model had prediction confidence of at least 97%, satisfying criterion 3. The model required few inputs, and these inputs were readily available. However, the parameters for the model were empirically derived from model output as described by Hill and Bolte (1987). This model was developed for anaerobic digesters, and the empirical parameters thus may not be applicable to predicting emissions from manure storages with no treatment.

Zeeman (1994; Table 3) developed a model to predict the production of CH_4 in manure storage using first-order hydrolysis of biodegradable polymers and Monod kinetics to simulate the

Table 3. Summary of empirical models simulating CH_4 emissions from manure storages.

Model	Model core equations[a]	Units
Chen and Hashimoto (1980)	$E_{CH4,man} = (B_oS_o/\theta) * [1 – (K/\theta\mu-1+K)]$ B_o = ultimate CH_4 yield S_o = influent volatile solids concentration θ = hydraulic retention time μ = maximum specific growth rate K = kinetic parameter	$L\ CH_4\ L^{-1}\ day^{-1}$
Hill (1991)	$E_{CH4,man} = \gamma * \tau * \sigma$ γ = specific CH_4 productivity τ = volatile solids reduction σ = organic loading rate stress factor	$L\ CH_4\ L^{-1}\ day^{-1}$
Zeeman (1994)	$E_{CH4,man} = \alpha * S_p$ α = first order hydrolysis constant S_p = concentration of biodegradable polymer substrate	$g\ CH_4\ L^{-1}\ day^{-1}$
Sommer et al. (2004)	$E_{CH4,man} = V_{s,d} * b_1 * \exp[\ln(A) – E*(1/R*T)] + V_{s,nd} * b_2 * \exp[\ln(A) – E*(1/R*T)]$ $V_{s,d}$, $V_{s,nd}$ = degradable and nondegradable volatile solids b_1, b_2 = rate correcting factors (1, 0.01) A = Arrhenius parameter E = activation energy R = universal gas constant T = temperature	$g\ CH_4\ day^{-1}$

[a] $E_{CH4,man}$ is the emission of CH_4 from manure storage as predicted by the various models. The units of $E_{CH4,man}$ vary for each model as listed under the units column.

growth of methanogenic bacteria. Zeeman's model was similar in concept to that of García-Ochoa et al. (1999), although much simpler. Unlike Hill (1991), experimentally-determined parameters were provided for both digested and fresh manure. The model satisfied criteria 1, 2, 3, and 5, and partially satisfied criterion 4. The model was accurate and capable of simulating reduction practices, but not completely consistent with the structure of IFSM.

Sommer et al. (2004; Table 3) simulated the production and emission of CH_4 from fresh manure storages. Like many of the models previously described, this model based CH_4 production on the degradation of VS. Additional factors affecting CH_4 production were temperature and storage time. This model also satisfied all five criteria. Unlike the other models, Sommer et al. (2004) was developed more generally for application to either digested or untreated manure.

Based on the above descriptions, we considered three of the six original models: Hashimoto et al. (1981), Zeeman (1994), and Sommer et al. (2004). We concluded that the model of Zeeman (1994) was less suitable than the remaining two. Zeeman used biologically-based equations to predict CH_4 production, but used emission factors or a similar method to predict the actual emission of CH_4. Sommer et al. (2004) also questioned whether the parameters published by Zeeman (1994) were derived solely from anaerobically-digested manure data.

Thus, the models of either Hashimoto et al. (1981) or Sommer et al. (2004) satisfied our criteria. The models were similar, with both based on the VS content of manure. Sommer et al. (2004) utilized the VS content in the manure storage, while Hashimoto et al. (1981) required the influent concentration of VS. Hashimoto et al. (1981) and subsequent publications (Hashimoto 1982b, 1983, and 1984) provided equations to calculate the empirical parameters as functions of temperature and VS concentration. Additionally, both Hashimoto et al. (1981) and Sommer et al. (2004) utilized relationships that account for the effect of temperature on emission rates. Finally, the scale of both models was consistent with that of IFSM. Although the model of Hashimoto et al. (1981) could be applied to fresh manure, several of the parameters were empirically determined based on data from anaerobic digesters. Sommer et al. (2004) employed commonly used empirical relationships (e.g., Arrhenius relationship) that were more general and thus more applicable to conditions outside of which they were developed. Additionally, Sommer et al. (2004) was a more recent model, incorporating more recent developments and data than Hashimoto's model. As a result, the model of Sommer et al. (2004) was selected.

A detailed description of the development of the chosen model is found in Sommer et al. (2004). This section briefly describes the model, how the parameters were determined, and how the model was integrated with IFSM.

Including factors for the conversion of units, manure storage CH_4 emission is predicted as:

$$E_{CH4,man} = \frac{24 \cdot V_{s,d} \cdot b_1}{1000} \cdot \exp\left[\ln(A) - \frac{E}{RT}\right] + \frac{24 \cdot V_{s,nd} \cdot b_2}{1000} \cdot \exp\left[\ln(A) - \frac{E}{RT}\right] \tag{4}$$

where $E_{CH4,man}$ is the emission of CH_4 from manure storage [kg CH_4 day^{-1}], $V_{s,d}$ and $V_{s,nd}$ are the degradable and nondegradable volatile solids [g], b_1 and b_2 are rate correcting factors [dimensionless], A is the Arrhenius parameter [g CH_4 kg^{-1} VS h^{-1}], E is the apparent activation energy [J mol^{-1}], R is the gas constant [J K^{-1} mol^{-1}], and T is the temperature [K] (Table 4).

From Sommer et al. (2004), the degradable volatile solids entering storage is:

$$V_{s,d} = V_{s,tot} \frac{B_o}{E_{CH4,pot}} \tag{5}$$

where $V_{s,tot}$ is the total volatile solids in the manure [g], B_o is the achievable emission of CH_4 during anaerobic digestion [g kg^{-1} VS] and $E_{CH4,pot}$ is the potential CH_4 yield of the manure [g kg^{-1} VS], which can be estimated using Bushwell's equation and the carbohydrate, fat, and protein content of the manure. For cattle slurry, Sommer et al. (2004) defined B_o as 0.2 g CH_4 kg^{-1} VS and $E_{CH4,pot}$ as 0.48 g CH_4 kg^{-1} VS.

Total volatile solids in the manure storage at any point in time is the difference between that entering the storage and that lost from the storage up to that point. That entering can be determined from the manure mass, the total solids content, and the volatile solids content:

$$V_{s,tot} = M_{manure} \cdot P_{TS} \cdot P_{VS} - V_{s,loss} \tag{6}$$

where M_{manure} is the accumulated mass of manure entering the storage [kg], P_{TS} is the total solids content in the manure [g TS kg^{-1} manure], P_{VS} is the fraction of volatile solids in the total solids [g VS g^{-1} TS], and $V_{s,loss}$ is the accumulated volatile solids lost. To obtain a similar rate of volatile solids loss as that reported by Sommer et al. (2004), this loss was determined as six times the methane loss from the stored manure.

The mass of nondegradable volatile solids, $V_{s,nd}$, is then calculated using a mass balance:

$$V_{s,nd} = V_{s,tot} - V_{s,d} \tag{7}$$

The inputs required for this model were the mass and temperature of the manure in storage. The amount of manure in the storage at a given time was modeled as the accumulation of that produced by the herd with daily manure excretion determined in the animal component of IFSM (Rotz et al., 1999). The temperature of the manure in storage on a given simulated day was estimated as the average ambient air temperature over the previous ten days. Both the manure quantity produced and daily air temperature were available in IFSM.

The relationships described above were generally applicable to uncovered slurry storages. Some farms use technology such as storage covers to reduce emissions. One such control includes the capture and burning of the CH_4 gas. This method greatly decreases the emission of CH_4, but also increases the emission of CO_2 through the combustion of CH_4. To simulate this storage treatment, the emission of CH_4 from an enclosed manure storage was calculated as:

$$E_{CH4,cov} = E_{CH4,man} \cdot \left(1 - \eta_{eff}\right) \tag{8}$$

where $E_{CH4,cov}$ is the CH_4 emitted from the enclosed manure storage [kg CH_4 day^{-1}], $E_{CH4,man}$ is the calculated emission of CH_4 from a storage with no cover using equation 4 [kg CH_4 day^{-1}], and η_{eff} is the efficiency of the collector [dimensionless]. The efficiency of the collector and flare was

Table 4. Parameters and values for the manure storage emissions model of Sommer et al. (2004).

Parameter	Variable	Value	Units
Volatile solids content[a]	P_{VS}	0.726, 0.698, 0.68[b]	g VS g^{-1} TS
Achievable CH_4[c]	B_o	0.2	g CH_4 g^{-1} VS
Potential CH_4[c]	$E_{CH4,pot}$	0.48	g CH_4 g^{-1} VS
Correcting factors[c]	b_1, b_2	1.0, 0.01	dimensionless
Arrhenius parameter[c]	ln(A)	43.33	dimensionless
Activation energy[c]	E	112,700	J mol^{-1}
Gas constant[c]	R	8.314	J K^{-1} mol^{-1}

[a] From USDA-SCS (1999).
[b] Values for heifers, dry cows, and lactating cows.
[c] From Sommer et al. (2004).

assumed to be 99% (EPA, 1999). The subsequent flaring of the captured CH_4 releases CO_2, which adds to the overall farm emission of this gas (Sedorovich, 2008). The additional emission of CO_2 due to the combustion of CH_4 is calculated as:

$$E_{CO2,flare} = E_{CH4,\mathrm{cov}} \cdot 2.75 \tag{9}$$

where $E_{CO2,flare}$ is the emission of CO_2 due to combustion of the CH_4 captured from the manure storage [kg CO_2 day^{-1}] and 2.75 is the ratio of the molecular weights of CO_2 and CH_4.

Field-applied Manure

Research has shown that field-applied slurry is a source of CH_4 emissions for several days after application, emitting between 40 to 90 g CH_4 ha^{-1} day^{-1} (Sommer et al., 1996; Chadwick and Pain, 1997; Sherlock et al., 2002). Emissions drastically decrease within the first three days, and soils return to a neutral source of CH_4 after 11 days (Sherlock et al., 2002).

Sherlock et al. (2002) related CH_4 emissions from field-applied slurry to the volatile fatty acids (VFAs) concentration in the soil. Because the VFAs in the soil were due to the application of the slurry (Sherlock et al., 2002), the model of Sherlock et al. (2002) was used to relate CH_4 emissions to the VFA concentration in the slurry as compared to the concentration in the soil. Therefore, emission of CH_4 from field-applied slurry is predicted as:

$$E_{CH4,app} = \left(0.170 \cdot F_{VFA} + 0.026\right) \cdot A_{crop} \cdot 0.032 \tag{10}$$

where $E_{CH4,app}$ is the emission of CH_4 from field-applied slurry [kg CH_4 day^{-1}], F_{VFA} is the daily concentration of VFAs in the slurry [mmol kg^{-1} soil], and A_{crop} is the land area [ha] where the manure is applied. Equation 10 is valid for CH_4 emissions within the first 11 days of application; after 11 days, CH_4 emissions are assumed to be negligible until the next application.

Sherlock et al. (2002) found that the daily VFA concentration exponentially decreased in the days following the application of manure slurry and approached background levels within approximately four days. Using this information, we derived a relationship predicting the daily concentration of VFA in the field-applied slurry.

$$F_{VFA} = F_{VFA,init} \mathrm{e}^{-0.6939 \cdot t} \tag{11}$$

where F_{VFA} is the daily concentration of VFAs in the slurry [mmol kg^{-1} slurry], $F_{VFA,init}$ is the initial concentration of VFAs in the slurry at the time of application [mmol kg^{-1} slurry], and t is the time since application [days], with t = 0 representing the day of application.

Paul and Beauchamp (1989) developed an empirical model relating the pH of manure slurry to VFA and total ammoniacal nitrogen (TAN) concentrations:

$$pH = 9.43 - 2.02 \cdot \frac{F_{VFA,init}}{F_{TAN}} \tag{12}$$

where pH is the pH of the manure slurry [dimensionless] and F_{TAN} is the concentration of TAN (NH_4^+ + NH_3) in the slurry [mmol kg^{-1} slurry]. Rearranging Equation 12, we obtained an equation predicting the initial concentration of VFAs based on the pH and TAN of the manure slurry:

$$F_{VFA,init} = \frac{F_{TAN}}{2.02}\left(9.43 - pH\right) \tag{13}$$

To predict an emission from field applied manure, Equation 13 was used to determine an initial VFA concentration and equation 11 was used to track the VFA concentration through time following field application. Using this concentration, an emission rate was determined until the remaining VFA concentration approached zero.

Grazing Animals

On farms that incorporate grazing for a portion of the year, freshly excreted feces and urine are directly deposited by animals on pastures. Studies have shown that feces are a small source of CH_4 and that emissions from urine are not significantly different from background soil emissions (e.g., Jarvis et al., 1995; Yamulki et al., 1999). Because animal-deposited feces contribute only minimally to overall farm CH_4 emissions, there were few data quantifying these emissions. A 2004 review of emissions from grazing animals concluded that CH_4 emission rates from freshly deposited feces were influenced by environmental conditions and animal rations, which were highly variable and unable to be represented by a constant emission rate (Saggar et al., 2004).

Despite this conclusion, we chose to use a constant emission factor to predict CH_4 emissions from feces deposited by grazing animals. The limited research data available and the relatively minor emission from this source did not justify using a more process-based model. As a result, a constant emission factor represented the best available approach. To determine this emission factor, we obtained emission rates from four published studies and used the average of 0.086 g CH_4 kg^{-1} feces for our emission rate (Table 5). For grazing systems, the daily emission of CH_4 was predicted as the product of this emission rate and the daily amount of feces deposited by grazing animals.

Table 5. Published and average emission rates of CH_4 emitted from feces directly deposited by animals on pasture lands**.**

Reference	Emission rate [g CH4 kg^{-1} feces]
Jarvis et al. (1995)	0.110
Flessa et al. (1996)	0.130
Holter (1997)	0.068
Yamulki et al. (1999)	0.036
Average	0.086

Barn Emissions

Manure on housing facility floors can be a source of CH_4 emissions. No published model or data were found for this emission source. As a result, unpublished CH_4 emissions data measured from barn floors (Varga et al., 2007) were used to develop an equation relating CH_4 emissions to the ambient temperature (R^2 = 0.56). The empirical model used was:

$$E_{CH4,floor} = \max(0.0,\ 0.14T + 0.29) \cdot A_{barn} \big/ 1000 \qquad (14)$$

where $E_{CH4,floor}$ is the daily rate of CH_4 emission from the barn floor [kg CH_4 day^{-1}], T is the ambient temperature [°C], and A_{barn} is the area of the barn floor covered with manure [m^2].

Equation 14 satisfies criteria 3 and 5 as an empirical equation that correlates CH_4 emission with temperature. We chose to use this relationship because it provided the best available information describing CH_4 emissions from barn floors. The temperature dependence of CH_4 production is well-documented (Zeikus and Winfrey, 1976; van Hulzen et al., 1999). As a function of temperature, equation 14 is a simplified, process-based equation, thus satisfying criterion 4 as well. This simple relationship predicted reasonable emission rates for ambient temperatures of 0°C and greater. Because this emission source is a relatively minor contributor to overall farm CH_4 emissions, development of a more detailed model was not justified.

Model Evaluation

Few data exist on overall emissions of CH_4 from dairy farms in the U.S. (Sedorovich et al., 2007). Studies that have quantified CH_4 emissions from specific farm sources often have not provided the specific data required to simulate scenarios in IFSM. In addition, these studies were often small-scale or laboratory studies that could not be adequately simulated. Therefore, we evaluated IFSM predictions of CH_4 emissions in three ways. First, for the major emission sources of enteric fermentation and manure storage, we compared observed data from previous studies to simulated emissions. We chose studies that represented typical emissions (Sedorovich et al, 2007), that included important input information required to simulate the observed conditions with IFSM and that were not a source of data in the development of the original model. Second, we performed a sensitivity analysis on the important parameters of the major model components. Finally, we used IFSM to simulate a representative farm and compared IFSM predictions to those previously identified as typical (Sedorovich et al., 2007).

Enteric Fermentation Emissions

To evaluate our model's ability to simulate CH_4 emissions due to enteric fermentation, we chose Kirchgessner et al. (1991) and Kinsman et al. (1995) as representative studies. Kirchgessner et al. (1991) measured CH_4 emissions from 67 lactating cows with an average weight of 583 kg and an average annual milk production of 6000 L cow^{-1}. The animals were fed diets consisting, on average, of 57% roughage composed of a mixture of grass hay and corn silage. They reported an average CH_4 emission of 300 g CH_4 cow^{-1} day^{-1} (± 39 g CH_4 day^{-1}), or 110 kg CH_4 cow^{-1} yr^{-1} (± 14 kg CH_4 cow^{-1} yr^{-1}). Using their average diet characteristics, cow weight, and target milk production, IFSM predicted 124 kg CH_4 cow^{-1} yr^{-1}. This simulated emission was within one standard deviation of the results reported by Kirchgessner et al. (1991), demonstrating that IFSM was capable of predicting CH_4 emissions from enteric fermentation.

Kinsman et al. (1995) measured CH_4 and CO_2 emissions from 118 lactating cows weighing an average of 602 kg with an average milk production of approximately 10,100 L cow^{-1} yr^{-1}. On average, animals were fed 17.5 kg DM animal^{-1} day^{-1} (± 1.4 kg DM animal^{-1} day^{-1}). The diet consisted of corn silage, alfalfa silage, hay, roasted soybean, barley, and other supplements. Kinsman et al. (1995) reported that CH_4 emissions ranged from 436 to 721 L CH_4 cow^{-1} day^{-1} (290 to 470 g CH_4 cow^{-1} day^{-1}) with an average rate of 587 L CH_4 cow^{-1} day^{-1} (390 g CH_4 cow^{-1} day^{-1}). Using similar diet characteristics and target milk production, IFSM predicted 420 g CH_4 cow^{-1} day^{-1}. This simulated emission was within the range, and close to the average, CH_4 emission rate reported by Kinsman et al. (1995), further demonstrating that IFSM could predict very reasonable CH_4 emissions from enteric fermentation. IFSM was also able to adequately predict CO_2 emissions from this same study (Sedorovich, 2008).

Manure Storage Emissions

We chose Husted (1994) as the representative study to test the ability of IFSM to predict CH_4 emissions from manure storages. Husted measured CH_4 emissions from slurry manure obtained from 160 Jersey cows and their calves that was stored in a 1200 m^3 outdoor tank. Over an annual period, CH_4 emissions from an uncovered storage ranged from about 5 to 35 g m^{-3} d^{-1} as slurry temperature varied from 6 to 18^{o}C. From the daily emission measurements, an annual emission of 15.5 kg animal^{-1} was estimated, which gave an annual emission from the storage of 2480 kg CH_4. The confidence limits of the data reflected an uncertainty of 30% in this estimate.

A representative farm was simulated with IFSM using the reported animal, manure and storage characteristics. The farm was simulated over 25 years of historical weather data from Thisted, Denmark (1974-1998). Over manure slurry temperatures of 6 to 18^{o}C, simulated daily CH_4 emissions were 4.7 to 34 g CH_4 m^{-3} d^{-1}, which agreed very well with measured values. Simulated average annual emissions ranged from 1,911 to 2,840 kg CH_4 with a 25 year average of 2,366 kg CH_4. These annual values were well within the uncertainty of Husted's estimated value, and the 25 year average emission was within 5% of his estimated annual emission. This comparison of simulated and measured emissions supports that the model predicts very reasonable emissions from stored cattle slurry manure.

Sensitivity Analysis

Models are more sensitive to some parameters and inputs than others; it is therefore important to quantify this sensitivity to ensure that values of variables with the most impact are accurate. A traditional sensitivity analysis involves varying a selected parameter by a selected percentage and calculating the percent change in the output. For example, to calculate how a 10% change in x affects the model output y, the original value of $x = x_{base}$ is used as an input to the model to obtain y_{base}. The parameter is then increased by 5% ($x_{+\%}$) and decreased by 5% ($x_{-\%}$) to obtain an overall change of 10%. The model output is determined at both of these values ($y_{+\%}$ and $y_{-\%}$) and the ratio of the change in y to the change in x is calculated as:

$$P_{change} = \left(\frac{y_{+\%} - y_{-\%}}{x_{+\%} - x_{-\%}} \right) \cdot \left(\frac{x_{base}}{y_{base}} \right) \tag{15}$$

A value of one indicates that a 10% change in y occurs with a 10% change in x; a lesser ratio indicates lesser sensitivity whereas a greater ratio indicates greater sensitivity. This method is useful when evaluating the sensitivity of variables with specific values (i.e., as opposed to categorical variables).

A traditional sensitivity analysis was performed on the modules developed for enteric fermentation, manure storage, and field-applied manure. To perform this analysis, the CH_4 model relationships were incorporated into an ad-hoc program using Matlab®. Modifications to the CH_4 relationships were made as necessary to achieve mathematically-correct and physically-realistic output while maintaining the scientific validity of the equations. Because a function was created for each emission source, the inputs and parameters were easily changed and the relevant outputs obtained. This method allowed the sensitivity of important parameters to be quantified while maintaining the interaction among variables. Sensitivity data generated in Matlab were compiled using a spreadsheet program with the overall sensitivity calculated using equation 15.

The enteric fermentation output was not highly sensitive to any of the model parameters. For a given percent change in the input, all of the parameters caused the same, or less, change in CH_4 emissions. The most important parameter was the maximum possible CH4 emission; the predicted emission rate was proportional to this assigned value (Table 6).

For the manure storage module, the majority of parameters had percent change values of 1.0. In other words, a given change in the input parameter caused the same change in the output (Table). However, the model was very sensitive to the Arrhenius parameter with a sensitivity greater than 100. The Arrhenius parameter accounts for the temperature dependency of CH_4 emissions from the storage. In the model, this parameter is not set by the user, but is an internally-set constant. Appropriate values for the Arrhenius parameters were determined by the original developers of the model by fitting the parameters to observed data. Additionally, the values selected ensured that annual CH_4 emissions from slurry storage corresponded to

Table 6. Sensitivity analysis results for the CH_4 module.

Manure storage			Field application			Enteric fermentation		
Variable[a]	%	Change[b]	Variable[a]	%	Change[a]	Variable[a]	%	Change[b]
P_{ts}, P_{vs}	25	1.0	M_{TAN}	25	0.99	MEI	25	0.7
B_o	25	0.98	M_{man}	25	0.01	$CH_{4,max}$	25	1.0
E_{maxCH4}	25	1.04[c]	pH	25	5.6	R_{diet}	25	0.2
b_1, b_2	25	0.99	Days	25	0.7[d]	C_{shape}	25	0.7
ln(A)[e]	25	>>100[e]	R_{app}	25	1.1[f]			
M_{man}	25	1.0						
T_{10C}	25	1.7						
T_{25C}	25	4.3						

[a] P_{ts}, P_{vs}: percent total solids and volatile solids (VS) [%]; B_o: achievable CH_4 yield [g CH_4 kg^{-1} VS; E_{maxCH4}: maximum potential CH_4 yield [g CH_4 kg^{-1} VS]; b_1, b_2: rate correction factor for degradable and nondegradable VS [unitless]; ln(A): Arrhenius parameter for inside and outside [g CH_4 kg^{-1} VS hr^{-1}]; M_{man}: mass of manure [kg]; T_{1OC}, T_{25C}: temperature [°C]; M_{TAN}: total ammoniacal nitrogen in manure [mmol kg^{-1} slurry]; pH: pH of the slurry [unitless]; days: days until incorporation [days]; R_{app}: manure application rate [kg m^{-2}]; MEI: metabolizable energy intake [MJ cow^{-1}]; CH_{4max}: maximum possible emission of CH_4 [MJ cow^{-1}]; R_{diet}: ratio of starch:ADF in diet [g g^{-1}]; and C_{shape}: shape parameter to calculate enteric fermentation.

[b] The value in the change column represents the percent the output changes based on the change in the input value. For example, if change = 1.0, then a 25% change in the input yielded a 25% change in the output.

[c] Varying E_{maxCH4} by 10% and 50% yielded 1.0 and 1.3, respectively.

[d] Varying Days by 10% and 50% yielded 1.7 and 0.5, respectively.

[e] The model was very sensitive to changes in the Arrhenius parameters for both inside and outside storage, with a change much greater than 100 for each parameter.

[f] Varying R_{app} by 10% and 50% yielded 1.0 and 1.3, respectively.

emissions calculated using IPCC emission factors (Sommer et al., 2004). As a result, the present Arrhenius values represent the best available model. Further studies quantifying CH_4 emissions from slurry storage are required to further evaluate and perhaps improve the calculation of this parameter (Sommer et al., 2004).

As with the manure storage model, most parameters in the field applied manure module caused approximately the same percent change in output as the change in input (i.e., sensitivity of 1.0). The pH of the manure slurry was the only variable that caused a major difference in the output, as evidenced by a five-fold change in output for a given change in input. Similar to the Arrhenius parameter, the pH of the slurry is not set by the user, but is an internal variable in IFSM. Currently, IFSM assumes that the pH of applied slurry is 8.0; future work may improve the prediction of CH_4 emissions by developing a prediction model for slurry pH.

The majority of CH_4 emissions from the farm were due to enteric fermentation. Even though the manure storage and field application modules were very sensitive to certain parameters, the impact of this sensitivity on farm emissions was small relative to enteric fermentation. Thus, changes to parameters in the manure storage and field application modules had a relatively small impact on farm GHG emissions; even though, some parameters were highly sensitive.

Representative Farm Emissions

As a final evaluation, simulated annual whole-farm emissions were compared to those previously summarized from prior literature for a hypothetical "typical" dairy farm in central

Pennsylvania (Sedorovich et al., 2007). Only a brief description of the farm is provided to document those assumptions most relevant to CH_4 production and emission. This representative farm included 100 Holstein cows (average mass of 650 kg), 38 heifers over one year in age (average mass of 470 kg), and 42 heifers under one year of age (average mass of 200 kg). Animals were housed in free-stall barns where they were fed total mixed rations consisting of corn, alfalfa and grass silages, high-moisture corn, and purchased supplemental feeds as required to meet animal nutrient needs. Manure was scraped daily, stored in a 3000 m^3 storage tank for up to six months, and applied to cropland in the spring and fall. On average over the whole year, the storage contained about 1200 m^3 of manure. The 89 ha farm area consisted of 19 ha of grass, 20 ha of alfalfa, and 50 ha of corn. Most of the crop nutrient requirements were met through manure nutrients generated on the farm, but nitrogen fertilizer was applied at rates of 50 and 65 kg ha^{-1} on corn and grassland, respectively.

Based upon the above farm characteristics, IFSM was used to simulate a representative farm on a clay-loam soil in central Pennsylvania using historical State College weather (1982-2006). The simulated annual emission from animals and housing facilities was 14,167 kg CH_4, primarily from enteric fermentation with a small emission (330 kg CH_4) from barn floors. Other emissions included 5,990 kg CH_4 from the manure storage and 20 kg CH_4 following field application of manure (Table 7). This gave a total annual emission of 20,177 kg CH_4 from this representative dairy farm. For an overall farm emission, this predicted rate was just 1% less than the rate of 20,365 kg CH_4 yr^{-1} that was estimated as a typical emission for a dairy farm of this size based upon the prior review of published emission data (Table 7). Overall, this comparison verifies that the model simulates CH_4 emissions very similar to those summarized from previous studies.

Model Application

Two whole-farm simulations were done to illustrate the use of the model for evaluating management impacts on CH_4 emissions from dairy farms. Important factors that affect CH_4 production include animal diets and the capture of CH_4 from the manure storage. The model was used to simulate the 100-cow representative dairy farm briefly described above, and then management changes were made to simulate higher forage diets and a covered manure storage with a flare to burn the biogas produced.

For the base farm, lactating cows were fed a relatively high grain diet. This has been a common practice in the past with relatively inexpensive grain for feed supplementation. With a recent

Table 7. A comparison of previously estimated and model predicted annual CH_4 emissions from a representative dairy farm in Pennsylvania.

	Representative farm[a] emissions [kg CH_4]	IFSM simulated emissions [kg CH_4]
Housing	13,324	14,167
Manure Storage	7,140	5,990
Croplands		
Grass	-27	--
Alfalfa	-52	--
Corn	-20	--
Total Cropland	-99	0
Field application	--	20
Total	20,365	20,177

[a]Emission rates were obtained from Sedorovich (2008). Total emissions were calculated using 183 LU in the herd and 1200 m^3 for average manure in storage with feed produced from 19 ha of grass, 20 ha of alfalfa, and 50 ha of corn.

increase in grain prices, there is incentive to feed more forage produced on the farm with less grain supplementation. This management change was simulated by switching the diet formulation for the lactating herd from a minimum forage to a maximum forage ration (Rotz et al., 1999). More of the corn produced on the farm was harvested as corn silage with less harvested as high moisture grain. This produced 115 Mg DM more forage and 50 Mg DM less grain for feeding the herd (Table 8). Total feed intake was increased about 2% with an annual average of 44 Mg DM less supplemental feed purchased and brought on to the farm. With the higher forage diets, animals produced about 21% more CH_4. This also increased the volatile solids content in the stored manure, which increased the emission from the storage by 6%.

This change also impacts the other greenhouse gas emissions of nitrous oxide (N_2O) and CO_2 (Sedorovich, 2008). Although the details of these processes are not presented here, the simulation indicates a small decrease in N_2O emission with greater use of corn silage. This occurs because more nitrogen is being removed in the corn silage and recycled through the animals. Carbon dioxide emission is also reduced with greater use of corn silage. With grain harvest, greater amounts of stover are left in the field, which creates greater microbial decomposition and ultimately more CO_2 emission. By removing the whole plant in corn silage harvest, less crop residue is left in the soil to enhance microbial respiration and the resulting CO_2 emission. Overall, this management change had very little effect on the total global warming potential of the greenhouse gases emitted from the farm (Table 8).

Table 8. Annual production, greenhouse gas emissions and economics of three production strategies on a simulated representative dairy farm in central Pennsylvania[a].

	High forage diet[b]	Low forage diet[c]	Enclosed manure storage[d]
Feed production and use, Mg DM			
Harvested forage	637	522	521
Harvested grain	109	159	159
Purchased feed	159	203	202
Total feed intake	905	884	882
Greenhouse gas emissions, kg			
Methane	23,475	20,177	14,251
Animal and barn floor	17,100	14,167	14,169
Manure storage	6,356	5,990	60
Field application	19	20	22
Nitrous oxide	668	685	494
Carbon dioxide	83,519	152,991	168,845
Net farm emission (CO_2 e)[e]	821,069	819,698	642,951

[a]100 Holstein cows producing 9,000 kg per cow of milk plus 80 replacement heifers housed year round in free stall barns with feed produced from 50 ha of corn, 20 ha of perennial grassland, and 19 ha of alfalfa.

[b] Lactating herd feed fed a maximum forage diet (60% of forage from corn silage) while maintaining 9,000 kg/cow milk production.

[c] Lactating herd feed fed a minimum forage diet (50% of forage from corn silage) while maintaining adequate fiber for 9,000 kg per cow milk production.

[d] Farm with low-forage diet and enclosed manure storage. Methane from storage is converted to CO_2 through combustion (99% efficiency).

[e]Total CO_2 equivalent greenhouse gas emission considering the global warming potential of CH_4 and N_2O to be 23 and 296 times that of CO_2, respectively.

With a tight cover on the manure storage, the CH_4 produced can be captured and burned. Combustion of the biogas transforms the CH_4 to CO_2. Since the CO_2 has 23 times less global warming potential, the net result is a reduction in greenhouse gas emission (Table 8). Methane emission from the storage is reduced by 99% while net farm CO_2 emission is increased 10%. Methane emission following field application is increased a small and unimportant amount. Covering the manure storage also eliminates N_2O emission from the storage by preventing any crusting on the manure surface (Sedorovich, 2008). The overall net effect of using this strategy is a 22% reduction in the total global warming potential of the whole-farm emission of greenhouse gases (Table 8).

Conclusions

Modules simulating CH_4 emissions from enteric fermentation, manure storage, field-applied manure, feces deposited in pasture, and manure on barn floors were developed and added to a farm simulation model (Integrated Farm System Model or IFSM). These new CH_4 modules incorporated the best available models that were consistent with our modeling objectives and with the current structure of IFSM. Model equations were based on previously published relationships and experimental data.

IFSM was shown to predict CH_4 emissions that were consistent with reported emissions from dairy farms, as well as from specific experiments quantifying emissions. A sensitivity analysis illustrated that model predictions responded appropriately to changes in model parameters.

With the incorporation of this CH_4 module, IFSM provides a tool for simulating whole-farm emissions of CH_4 and evaluating the overall impact of management scenarios used to reduce emissions. Farm simulations showed that increasing the use of forage (corn silage) in animal diets increased CH_4 emission by 17% with little impact on the global warming potential of net farm emissions of all greenhouse gases. Using a manure storage cover and burning the CH_4 reduced farm emission of CH_4 by 30% with a 22% reduction in the total global warming potential of the whole-farm emission of greenhouse gases.

References

Baldwin, R.L., J.H.M. Thornley, and D.E. Beever. 1987. Metabolism of the lactating cow. II Digestive elements of a mechanistic model. *J. Dairy Res.* 54:107-131.

Benchaar, C., J. Rivest, C. Pomar, and J. Chiquette. 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. *J. Anim. Sci.* 76:617-627.

Blaxter, K.L. and J.L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. *Br. J. Nutr.*19:511-522.

Chadwick, D.R. and B.F. Pain. 1997. Methane fluxes following slurry applications to grassland soils: laboratory experiments. *Agr. Ecosyst. Environ.* 63:51 – 60.

Chen, Y.R., and A.G. Hashimoto. 1980. Substrate utilization kinetic model for biological treatment processes. *Biotechnol. Bioeng.* 22: 2081 – 2095.

Dijkstra, J., H. D. St.C.Neal, D.E. Beever, and J. France. 1992. Simulation of nutrient digestion, absorption, and outflow in the rumen: Model description. *J. Nutr.* 122:2239-2256.

Energy Information Administration (EIA). 2006. Emissions of greenhouse gases in the United States 2005. DOE/EIA-0573 (2004). U.S. Department of Energy, Washington, D.C. Available at: http://www.eia.doe.gov/oiaf/1605/ggrpt/. Accessed 12 November 2007.

EPA. 1999. U.S. methane emissions 1990 – 2020: Inventories, projections, and opportunities for reductions. EPA 430-R-99-013. U.S. Environmental Protection Agency, Washington, D.C. Available at: http://www.epa.gov/ghginfo. Accessed 23 November 2007.

FAO. 2006. Livestock's long shadow. H. Steinfeld, P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan, eds. Rome, Italy: FAO.

Flessa, H. P. Dörsch, F. Beese, H. Konig, and A.F. Bouwman. 1996. Influence of cattle wastes on nitrous oxide and methane fluxes in pasture land. *J. Environ. Qual.* 25: 1366 – 1370.

García-Ochoa, F., V.E. Santos, L. Naval, E. Guardiola, and B. López. 1999. Kinetic model for anaerobic digestion of livestock manure. *Enzyme Microb. Tech.* 25:55-60.

Hashimoto, A.G. 1982a. Effect of mixing duration and vacuum on methane production rate from beef cattle waste. *Biotechnol. Bioeng.* 24: 9-23.

Hashimoto, A.G. 1982b. Methane from cattle waste: Effects of temperature, hydraulic retention time, and influent substrate concentration on kinetic parameter (K)*. *Biotechnol. Bioeng.* 24:2039-2052.

Hashimoto, A.G. 1983. Conversion of straw-manure mixtures to methane at mesophilic and thermophilic temperatures. *Biotechnol. Bioeng.* 25: 185-200.

Hashimoto, A.G. 1984. Methane from swine manure: Effect of temperature and influent substrate concentration on kinetic parameter (K)*. *Agr. Wastes.* 9:299-308.

Hashimoto, A.G., V.H. Varel, and Y.R. Chen. 1981. Ultimate methane yield from beef cattle manure: Effect of temperature, ration consituents, antibiotics and manure age. *Agr. Wastes* 3:241-256.

Hill, D.T. 1982. A comprehensive dynamic model for animal waste methanogensis. *Trans. ASAE* 28(3):850-855.

Hill, D.T. 1991. Steady-state mesophilic design equations for methane production from livestock wastes. *Trans. ASAE* 34(5):2157-2163.

Hill, D.T. and J.P. Bolte. 1987 Modelling fatty acid relationships in animal waste anaerobic digesters. *Trans. ASAE* 30(2):502-508.

Holter, P. 1997. Methane emissions from Danish cattle dung pats in the field. *Soil Biol. Biochem.* 29(1): 31 – 37.

Husted, S. 1994. Seasonal variation in methane emission from stored slurry and solid manure. *J Environ. Qual.* 23:585-592.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds. United Kingdom and New York, NY, USA: Cambridge University Press.

Jarvis, S.C., R.D. Lovell, and R. Panayides. 1995. Patterns of methane emission from excreta of grazing animals. *Soil Biol. Biochem.* 27(12):1581 – 1588.

Kebreab, E., K. Clark, C. Wagner-Riddle, and J. France. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Can. J. Anim. Sci.* 86:135-158.

Keppler, F. and T. Röckmann. 2007. Methane, plants, and climate change. *Sci. Am.* Vol:52-57.

Kinsman, R., F.D. Sauer, H.A. Jackson, and M.S. Wolynetz. 1995. Methane and carbon dioxide emissions from dairy cows in full lactation monitored over a six month period. *J. Dairy Sci.* 78:2760-2766.

Kirchgessner, M., W. Windisch, H.L. Müller, and M. Kreuzer. 1991. Release of methane and of carbon dioxide by dairy cattle. *Agribiol. Res.*, 44(2-3):91-102.

Külling, D.R., H. Menzi, F. Sutter, P. Lischer, and M. Kreuzer. 2003. Ammonia, nitrous oxide and methane emissions from differently stored dairy manure derived from grass- and hay-based rations. *Nutr. Cycl. Agroecosyst.* 65:13 – 22.

Lovett, D.K., L. Shalloo, P. Dillon, F.P. O'Mara. 2006. A systems approach to quantify greenhouse gas fluxes from pastoral dairy production as affected by management regime. *Agr. Syst.* 88:156 – 179.

Madigan, M.T., J.M. Martinko, and J. Parker. 2003. Brock biology of microorganisms. NJ:Prentice Hall.

Mills, J.A.N., J. Dijkstra, A. Bannink, S.B. Cammell, E. Kebreab, and J. France. 2001. A mechanistic model of whole-tract digestion and methanogenesis in the lactating dairy cow: Model development, evaluation, and application. *J. Anim. Sci.* 79:1584-1597.

Mills, J.A.N., E. Kebreab, C.M. Yates, L. A. Crompton, S. B. Cammell, M.S. Dhanoa, R.E. Agnew, and J. France. 2003. Alternative approaches to predicting methane emissions from dairy cows. *J. Anim. Sci.* 81(12):3141-3150.

Moe, P.W. and H.F. Tyrrell. 1979. Methane production in dairy cows. *J. Dairy Sci.* 62:1583-1586.

Monteny, G.J., C.M. Groenestein, and M.A. Hilhorst. 2001. Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutr. Cycl. Agroecosyst.* 60:123-132.

NRC. 2001. Nutrient requirements of dairy cattle. 7th ed. Washington, D.C.:National Academy Press.

Paul, J.W. and E.G. Beauchamp. 1989. Relationship between volatile fatty acids, total ammonia, and pH in manure slurries. *Biol. Waste.* 29:313 – 318.

Rotz, C.A., M.S. Corson, and C.U. Coiner. 2007. *Integrated Farm System Model: Reference Manual*. Pasture Systems and Watershed Management Research Unit, USDA Agricultural Research Service: University Park, PA. Available at: http://www.ars.usda.gov/Main/docs.html?docid=8519. Accessed 31 October 2007.

Rotz, C.A., D.R. Mertens, D.R. Buckmaster, M.S. Allen, and J.H. Harrison. 1999. A dairy herd model for use in whole farm simulations. *J. Dairy Sci.* 82(12):2826 – 2840.

Saggar, S., N.S. Bolan, R. Bhandral, C.B. Hedley, and J. Luo. 2004. A review of emissions of methane, ammonia, and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. *New Zeal. J. Agr.* 47: 513 – 544.

Sedorovich, D.M. 2008. Greenhouse gas emissions from agroecosystems: simulating management effects on dairy farm emissions. Unpublished PhD diss. University Park, PA: The Pennsylvania State University, Department of Agricultural and Biological Engineering.

Sedorovich, D.M., C.A. Rotz and T.L. Richard. 2007. Greenhouse Gas Emissions from Dairy Farms. ASABE Paper No. *074096*. St. Joseph, Mich.: ASABE.

Schils, R.L.M., A. Verhagen, H.F.M. Aarts, and L.B.j. Sebek. 2005. A farm level approach to define successful mitigation strategies for GHG emissions from ruminant livestock systems. *Nutr. Cycl. Agroecosyst.* 71:163 – 175.

Sherlock, R.R., S.G. Sommer, R.Z. Khan, C.W. Wood, E.A. Guertal, J.R. Freney, C.O. Dawson, and K.C. Cameron. 2002. Emission of ammonia, methane and nitrous oxide from pig slurry applied to a pasture in New Zealand. *J. Environ. Qual.* 31:1491-1501.

Sommer, S.G., S.O. Petersen, and H.B. Møller. 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutr. Cycl. Agroecosyst.* 69:143-154.

Sommer, S.G., R.R. Sherlock, and R.Z. Khan. 1996. Nitrous oxide and methane emissions from pig slurry amended soils. *Soil Biol. Biochem.* 28(10/11):1541 – 1544.

van Hulzen, J.B., R. Segers, P.M. van Bodegom, and P.A. Leffelaar. 1999. Temperature effects on soil methane production: an explanation for observed variability. *Soil Biol. Biochem.* 31:1919 – 1929.

Varga, G.A., R.E. Graves, J. Heinrichs, and E.F. Wheeler. 2007. Unpublished data from *Reducing ammonia emissions from dairy farms – Evaluating whole farm strategies*. USDA Special Grants 2004-2007. University Park, PA: The Pennsylvania State University.

Wilkerson, V.A., D.P. Casper, and D.R. Mertens. 1995. The prediction of methane production of Holstein cows by several equations. *J. Dairy Sci.* 78:2402-2414.

Yamulki, S., S.C. Jarvis, and P. Owen. 1999. Methane emission and uptake from soils as influenced by excreta deposition from grazing animals. *J. Environ. Qual.* 28: 676 – 682.

Yates, C.M., S.B. Cammell, J. France, and D.E. Beever. 2000. Prediction of methane emissions from dairy cows using multiple regression analysis. *Proc. Br. Soc. Anim. Sci.* 2000:94.

Zeeman, G. 1994. Methane production/emission in storages for animal manure. *Fert. Res.* 37:207-211.

Zeikus, J.G., and M.R. Winfrey. 1976. Temperature limitation of methanogenesis in aquatic sediments. *Appl. Environ. Microbiol.* 31:99 – 107.